CHANGES ON THE COLORADO RIVER:

OPERATING GLEN CANYON DAM FOR ENVIRONMENTAL CRITERIA

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ABSTRACT

Historically, dams have been built and operated for meeting water delivery, flood control, and/or hydroelectric development. Rarely have environmental considerations been brought into the equation for maintenance or restoration of critical ecosystem species or processes. Since 1989, the Bureau of Reclamation has been involved in evaluating future operations at Glen Canyon Dam on the Colorado River. The intent of this evaluation is to satisfy NEPA compliance concerns and to serve as a template for future balancing of dam management with the needs of the downstream ecosystem.

The Grand Canyon exists immediately below Glen Canyon Dam and was formed by the natural flows of the Colorado River. The environmental and physical resources are dynamic and continually responding to changes in the controlling factors of water release and water quality. The Bureau of Reclamation is developing an adaptive management approach to the future operations of Glen Canyon Dam. The future focus of adaptive management will be to find ways through operations and physical modifications to utilize the resources at the dam to meet our social obligations, and also to maintain and restore critical elements in the Grand Canyon ecosystem.

Specific physical and operational options being evaluated include the addition of selective withdrawal structures on Glen Canyon Dam, reduction in peaking flows, modification of seasonal flow volumes, sediment stabilization, and watershed management.

A long-term monitoring program with cooperative environmental data bases and geographic information system is being developed for future comparisons. With a proper understanding of the terrestrial and aquatic ecosystems, opportunities for ecosystem restoration can be realized.

INTRODUCTION

Dams, diversions and other forms of flow regulation are common anthropogenic alterations of river ecosystems (Ward and Stanford 1979, Lilliehammer and Saltveit 1984), particularly in arid lands where economic growth requires development of water resources for agriculture, urban supplies and hydroelectric power. Many developed regions (e.g. northern Europe, Australia, North America, Japan) have regulated virtually all of their rivers (Gore and Petts 1989), and developing regions are quickly following suit. Despite the great advances in dam design and construction techniques during the past century, research on the ecosystem impacts of flow regulation is comparatively recent, especially that on large rivers (Minshall et al. 1992).

Improved management of regulated rivers requires integration of information on hydrology, sediment transport, water quality, aquatic and riparian ecology, and land use. Flow regulation impacts on river ecosystems vary on the basis of: different types of rivers (e.g. geologically constrained *versus* unconstrained, Mosely 1987); different types of flow regulation structures and operating policies of dams (Armitage 1984, Risser and Harris 1989); the potential for ecosystem restoration based on the location of dams in the drainage basin (Ward and Stanford 1983); and according to land use practices in the watershed (e.g. management for economic gain *versus* environmental criteria). Some of these dam impacts are related to the physical presence of the dam, while others are related to dam operations.

Here we discuss efforts by the Bureau of Reclamation's Glen Canyon Environmental Studies (GCES) to apply scientific information to improvement of Colorado River ecosystem management downstream from Glen Canyon Dam. We describe: (1) Colorado River basin geography and climate; (2) the history and policies of flow regulation in this large, aridlands river basin, (3) river ecosystem changes engendered by flow regulation; (4) the integration of physical, biological and socio-economic studies into the congressionally mandated Glen Canyon Dam Environmental Impact Statement (GCD-EIS) for future management; and (5) the challenges and un-certainties in developing and implementing an adaptive management approach for this system. The study of flow regulation impacts, and the potential for, and limits of, ecosystem management and restoration, is best undertaken in parks where other human disturbances are limited (e.g. grazing, mining, urbanization). Flow regulation affects more than 30 large parks in the United States (Jackson et al. 1992), and the Colorado River downstream from Glen Canyon Dam is a premier example of an ecosystem with few anthropogenic disturbances other than flow regulation. The focus of our efforts there are linking scientific knowledge to the development of specific management strategies and activities, including: preservation or restoration of essential or irreplaceable natural components; protection of valued resources and processes; limiting the expansion of non-native species and processes; and management of renewable resources for sustainability.

GEOGRAPHY OF THE COLORADO RIVER BASIN

Precipitation is limited and variable on the continental, arid climate of the topographically diverse Colorado Plateau, where nearly 90% of incoming precipitation is lost to evaporation (Iorns et al. 1965, Sellers and Hill 1974). Fed by Rocky Mountain snowmelt and draining the 373,000 km^2 Colorado Plateau, the Colorado River is the primary source of surface water in the American Southwest. Geomorphically, the river is deeply incised into the largely sedimentary strata of the Colorado Plateau in the Grand Canyon, and is classified as approximately a ninth order stream. Lees Ferry (defined by convention as km 0, and 24.6 km downstream from Glen Canyon Dam) lies near the political boundary between the upper and lower Colorado River basins (Figure 1). The river drains nearly 110,325 km^2, flows 470 km and descends at least 578 m through Sonoran and Mohave Desert desertscrub and riparian vegetation in lower Glen Canyon and all of Grand Canyon (Warren et al. 1982). Land and resource management in the study reach is the responsibility of the National Park Service and several Native American tribes. Surrounding land uses on the sparsely populated Colorado Plateau include grazing, timber harvest, mining and recreation.

Downstream from Glen Canyon Dam, the Colorado River is a geologically constrained, eddy-dominated river (Howard and Dolan 1981). Bedrock geology largely controls reach characteristics, including width and depth ratios (Schmidt and Graf 1990). The river's infamous rapids are situated at the mouths of some of its more than 330 tributaries (Kieffer 1985). The river's more than 45 perennial tributaries in the Grand Canyon region contribute less than 15 m^3/s (<3.5%) to the mainstream at baseflow; however, all tributaries can occasionally deliver large quantities of sediment to the river, either through floods or debris flows (Webb et al. 1989, Graf et al. 1991). The larger perennial streams (especially the Paria River, the Little Colorado River, and Kanab Creek) contribute high concentrations of fine sediments. Mainstream (pre-dam) and tributary-derived alluvial fine sands are deposited in geomorphically prescribed settings in and around the river's eddies, thereby controlling the distribution of backwater and riparian habitats (Schmidt and Graf 1990, Stevens et al. in press). Colorado River sandbars do not migrate as in alluvial rivers, but remain associated with specific geomorphic controls (Rubin et al. 1990).

Prior to the closure of Glen Canyon Dam in 1963, the Colorado River through the Grand Canyon was turbid, seasonally flood prone and seasonally warm, with little daily flow fluctuation (Howard and Dolan 1981, Blinn and Cole, 1991). Annual spring and summer floods scoured the river corridor, transporting an annual average of 60 million metric tons (mt) of sediment through the Grand Canyon (Andrews 1991), and annually recreating large, unvegetated sandbars and return current channel backwaters, especially in the wide reaches of the river. Pre-dam water temperature at Lees Ferry ranged from freezing in winter to more than 29°C in mid-summer.

COLORADO RIVER REGULATION AND ADMINISTRATION

The Colorado River is one of the most thoroughly regulated rivers in the United States (Hirsch et al. 1990). The river's flow through 14 federal dams and more than 30 non-federal regulating features is legally controlled through a large body of laws, compacts and treaties known as the "Law of the River" (Goslin 1982; Table 1). The Colorado River Compact divides the Colorado River into upper (Wyoming, Colorado, Utah, New Mexico) and lower (Arizona, Nevada, California) basins, and defines the amount of water the lower basin and Mexico receive. The upper basin is required to release an average of 10.15 km^3 of water annually to the lower basin. The lower basin must release 1.85 km^3 to Mexico annually. The Secretary of the Interior is the defined water master for the Colorado River. An Annual Operating Plan is developed yearly by the basin states and the federal government to coordinate reservoir management and dam release schedules. Although the 1922 Colorado River Compact was based on an estimated annual runoff of 18.5 km^3, subsequent studies have demonstrated that mean basin yield is nearer 14.8 km^3. Failure to adjust adjudicated flow volumes to the actual hydrology has increased concern over Compact allocations.

The Colorado River was initially impounded by Hoover Dam in 1935, forming Lake Mead, and by Glen Canyon Dam in 1963, forming Lake Powell. Glen Canyon Dam construction took place from 1956 to 1963, following authorization in the Colorado River Storage Project Act in 1956 (United States Water and Power Resources

Service 1981; Table 1). Lake Powell is the second largest reservoir in the United States, and impounds 33.3 km^3 of water in 290 km-long Lake Powell in Utah and Arizona. Lake Powell stores 80% of the upper basin's water and is used for water storage, hydroelectric power production, and recreation. The dam's eight turbines have a combined capacity of 1,340,000 KW, providing hydroelectric energy to 180 utility companies and more than five million consumers throughout the basin states. The dam generates approximately $280 million of revenue annually from hydroelectric power generation.

FLOW REGULATION IMPACTS

Construction and operation of Glen Canyon Dam generated complex, long-term, unanticipated changes in ecological processes and components in the Colorado River ecosystem (Miller et al. 1983, Patten 1991). Inundation of the Glen Canyon basin beneath Lake Powell eliminated 92% of the 300 km-long Glen Canyon, and created a novel, lacustrine ecosystem with large seasonal stage changes (Ward and Stanford 1991). Downstream, the dam reduced the frequency, duration, magnitude and seasonal timing of flow and scouring floods (Table 2). Mean flow has decreased slightly from 470 m^3/s in pre-dam time to 412 m^3/s after 1963, and post-dam maximum flow rarely exceeds powerplant capacity (940 m^3/s). Annual peak flow was reduced from 2,194 m^3/s to 839 m^3/s, and 10-year return frequency flood flows were reduced from 3,545 m^3/s to 1,850 m^3/s. Post-dam flows have historically fluctuated widely for peak hydropower production, creating daily "tides" of more than 3 m in the river corridor.

Cessation of annual flooding and sediment trapping in Lake Powell has led to a reduction in the supply of sediment to the river system. Clear water releases from the dam have induced erosion of existing sandbars and sediments stored in the channel, and armoring of the bed in the first 25 km downstream from the dam. Erosion occurs through three primary mechanisms: ubiquitous seepage erosion, velocity-related tractive erosion, and local wave action (Beus and Avery 1992, Carpenter et al. 1995).

Hypolimnetic releases from deep within Lake Powell have resulted in decreased mean and variability of temperature. With the impacts of reduced flood frequency and altered flow regimes, decreased sediment transport, and alteration of the river's temperature taken into account, it is apparent that flow regulation at Glen Canyon Dam has essentially decoupled the Colorado River hydrograph from the climate.

Dam-induced increased water clarity in the tailwaters reach between Glen Canyon Dam and the Paria River confluence (km 1; Yard et al. 1993), as well as decreased flood frequency and predictability, has increased the proportion of firm substrata on the channel bed, and reduced mean and variance of water temperature. These physical changes have collectively promoted production of the benthic green filamentous alga, Cladophora glomerata, in the upper reaches (Hardwick et al. 1992, Blinn and

Cole 1991). _Cladophora_ is not consumed to any significant extent by benthic invertebrates; rather, _Cladophora_ filaments structurally support epiphytic diatoms, which, in turn, serve as food for high densities but low diversities of aquatic invertebrates (especially native Chironomidae and introduced _Gammarus lacustris_; Blinn et al. 1992, Angradi 1994).

Downstream from the Paria River, low water clarity reduces benthic standing mass by more than an order of magnitude, and _Oscillatoria_ spp. (Cyanobacteria) and _Simuliium arcticum_ dominate the benthic assemblage (Blinn et al. 1992). Fluctuating flows desiccate _Cladophora_ beds and restrict its growth to below the minimum discharge stage (Angradi and Kubly 1994, Blinn et al. in press). Fluctuating flows offer a selective advantage to the _Oscillatoria_ assemblage because of its ability to withstand exposure to the atmosphere (Blinn et al. in press).

The Colorado River fishery below the dam reflects numerous human impacts (Minckley 1991). The tailwaters fisheries in the first 25 km is dominated by introduced rainbow trout (_Onchorynchus mykis_), which rely on the _Cladophora_/epiphyte/invertebrate food chain. Native fish reach maximum densities in the middle reaches of the river. In the lower Grand Canyon, native fish densities are reduced and native species are replaced by non-native carp, catfish and striped bass.

Several novel ecological shifts have developed in the river corridor that demonstrate that Glen Canyon Dam has increased linkage between aquatic and riparian domains in this regulated river. Bald eagle and waterfowl concentrate in the highly productive upper reaches during winter (Brown et al. 1989, Stevens and Kline 1991). A breeding waterfowl population has developed in the upper Canyon reaches since 1982 (Brown et al. 1987, Brown and Trossett 1989, Stevens and Kline 1991). Grand Canyon waterfowl and riparian avifauna (below) provide the food base to support the largest breeding peregrine falcon population in the 48 conterminous states (Brown et al. 1992).

In the riparian realm, reduced flood frequency has resulted in rapid colonization of shoreline habitats by fluvial marsh vegetation (Stevens et al. in press), and by largely non-native lower riparian zone vegetation (i.e. _Tamarix_ _ramosissima_, _Alhagi_ _camelorum_ and _Salsola_ _iberica_; Turner and Karpiscak 1980, Johnson 1991). Large hourly flow fluctuations from 1964 to 1991 (except for 1983 to 1986) has led to coarser soil texture (Stevens and Waring 1985) and reduced nutrient availability on bar platforms (Stevens 1989). Limited nutrient availability and coarser soil texture has reduced the germination success of _Tamarix_. A consequence of these changes is a succession towards clonal herbaceous and woody plant taxa (both native and non-native) is occurring along the Colorado River sandbars (Stevens 1989).

THE GLEN CANYON ENVIRONMENTAL STUDIES AND DAM EIS

The Glen Canyon Environmental Studies (GCES) Program was authorized by the Department of the Interior on 8 December, 1982. The GCES Program underwent three phases (Table 1). Phase I involved the compilation of basic information on specific ecosystem components. GCES Phase II involved ecosystem research on the impacts of low and fluctuating flows (Patten 1991; Figure 2). Phase III , the current effort, is focusing on evaluation of reduced flow fluctuations, consolidation of scientific information, and development of a long-term monitoring program. The scientific efforts will form the basis for the Glen Canyon Dam adaptive management program.

The Secretary of the Interior authorized an ex post facto Environmental Impact Statement on Glen Canyon Dam operations (GCD-EIS) effects on downstream resources on 27 July, 1989. The GCD-EIS objectives were to evaluate alternatives to future operation and attempt to optimize environmental and economic benefits of the dam. This process embraces the numerous conflicting agency mandates and opinions regarding appropriate management (Wegner 1991, Figure 2). During initial scoping sessions, this interagency, multi-disciplinary GCD-EIS received the second largest number of public comments of any EIS in U.S. history. The final GCD-EIS is the result of 5.5 yr of discussion between numerous agencies, eight Native American tribes and the public (United States Bureau of Reclamation 1995).

The GCES scientific program has demonstrated that seasonal variability of flows is an important element in river ecosystem sustainability. Natural river ecosystems are inherently unpredictable and complex. The GCD-EIS Preferred Alternative recommends reduced flow magnitude and release rates to store a mass balance of sediment in the main channel, coupled with controlled floods (high water releases) to restore elevated sand deposits and backwater habitats. The GCD-EIS also recommends implementation of an adaptive management approach to improve river ecosystem management over time. Based on results of on-going research and short-term and long-term monitoring of critical resources, adaptive management of Glen Canyon Dam will provide for continuing evaluation, improvement and refinement of dam operations over time.

Implementation of a flow regime that stores a mass balance of tributary-derived sediment in the channel, coupled with periodic planned floods to redistribute that sediment, is an environmentally and economically rational strategy. To protect river corridor resources during completion of the GCD-EIS, and as a test of the mass balance concept, Interim Flows (reduced flow fluctuation and release rates) were initiated on 1 August, 1991. Interim flows are at least partially successful. Interim Flows are similar to those proposed in the Preferred Alternative, and will remain in effect until implementation of the Secretary of the Interior's Record of Decision on dam operations.

Despite implementation of Interim Flows and completion of the GCD-EIS, numerous issues remain unresolved, including potential loss of resources in the tailwaters reach between the dam and the Paria River (km 1.0), uncertainty regarding future inflow, the frequency and magnitude of flooding required to restore sandbars and backwater habitats, the mechanics of backwater formation, and long-term changes in the flow regime as Lake Powell fills with sediment. Restoration of endangered fish (e.g. humpback chub) by increasing flood frequency may conflict with habitat availability for endangered Kanab ambersnail and endangered Southwest willow flycatcher. Also, further unanticipated changes are expected as regional physical and social conditions change, and as additional novel species (e.g. parasites, disease organisms and weed species) continue to colonize this ecosystem. Dynamic ecosystems require similarly dynamic management strategies, which we hope the proposed GCD-EIS adaptive management approach will provide.

MANAGEMENT IMPLICATIONS AND SUMMARY

Management of this highly altered river ecosystem for the natural condition is impeded by two factors. First, knowledge of the pre-dam "natural" ecosystem condition is poorly unknown: insufficient data exist on diversity, population dynamics and distribution of most of the flora and fauna to accurately portray the pre-dam condition, which had already been altered by the introduction of non-native fish, invertebrates and plant species. Second, reestablishing the natural, highly variable flow regime is not possible because upstream diversions will remove 20% of the flow over the next two decades, and numerous sediment-trapping impoundments have permanently reduced flood magnitude, flood frequency and sediment transport. Therefore, even were the dam to be removed (an option rejected early in the GCD-EIS scoping process), natural conditions could not be restored.

Biological losses in this system have occurred since closure of the dam in 1963, including: an unknown benthic invertebrate assemblage; four native fish species; river otter (<u>Lutra canadensis</u> <u>sonora</u>; native lower riparian zone Goodding willow (Salix gooddingii); and the long-term loss of upper riparian zone vegetation (Table 2). Insufficient data exist to hypothesize about the status of pre-dam mainstream invertebrates. The native fisheries may be partially recovered, depending on the success of non-native fish management and thermal management through multi-level withdrawal (United States Bureau of Reclamation 1995); however, the dominance of non-native fish in the more-or-less natural lower Green River and Cataract Canyon upstream from Lake Powell, and elsewhere throughout the system, indicates the probability of recovery is low. River otter were initially rare in the Colorado River and probably are not recoverable because of their susceptibility to inbreeding depression at low population densities. Recovery of mainstream Goodding willow is unlikely because of high mortality rates and the probable increase in post-dam beaver populations, as well as failure of recruitment due to flood control and increased coarseness of riparian soil texture. Loss of pre-dam vegetation could be overcome with artificial planting and maintenance if the land managers pursued that labor-intensive strategy. Lastly, it is important to manage the non-native river corridor vegetation to prevent non-native species from further invading the Grand Canyon's many pristine watersheds and springs, because there are few pristine streams and springs left to study in the United States.

When viewed in a landscape or regional context, the biological losses in this system are offset by large gains in productivity, diversity, and other post-dam river ecosystem attributes, including: increased benthic production; a trophy trout fishery; substantially increased wetland and riparian vegetation; increased winter bald eagle and waterfowl populations; increased breeding waterfowl, peregrine falcon, and riparian passerine populations; and improved recreational conditions. Many of these unanticipated developments in post-dam aquatic and riparian assemblages in Grand Canyon offset population losses threatened by rapid economic development elsewhere in the West (e.g. Dahl 1990). These resources are valued by various politically active public groups and we suggest that their management should not be carefully considered.

The bias that "natural is best" is overwhelmingly apparent in our culture, from childbirth practices to organic food advertisements and baseball stars. This sentiment is the foundation of the 1916 National Park Service Organic Act and the Endangered Species Act (1973). The pursuit of such ideals is a quixotic undertaking; however, such pursuits may fail because critical processes and linkages have inexorably changed, and because valued, novel changes go unrecognized. Therefore, attempting to return the Colorado River ecosystem to an unknown and technically unachievable natural condition with high flood disturbance, low diversity and low productivity may not be the most rational management goal.

We have a unique opportunity at Glen Canyon Dam to develop a new and innovative perspective on cooperative ecosystem management; however, the political volatility of Colorado River management is unlikely to result in a clear and logical consensus on the desired state of this regulated river ecosystem. Therefore, the adaptive management approach recommended in the GCD-EIS will at least provide the forum for continued debate on dam and resource management. The adaptive management approach provides a mechanism by which we can link scientific information on the responses of this world renown ecosystem to responsible management actions. Understanding the influences of flow regulation on rivers is essential if we are to maintain sustainable river ecosystems for future generations.

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Table 1: The legal and administrative history of Colorado River management (Goslin 1982, in part).

YEAR	EVENT
1902	The Bureau of Reclamation was created.
1904	Grand Canyon was declared a National Game Reserve (T. Roosevelt).
1919	Grand Canyon was declared a national park.
1921	The name "Colorado River" was officially applied to the river downstream of the Upper Colorado and Green river confluence.

1922	The Colorado River Compact allocated the river's water between the upper (Wyoming, Colorado, Utah and New Mexico) and lower (Arizona, Nevada and California) basins, and protected previously unadjudicated upper basin consumptive uses.
1923	United States Geological Survey surveyed potential Colorado River dam sites (La Rue 1925).
1928	The Boulder Canyon Project Act authorized construction of Hoover Dam, limited California use of water to 4.4 million acre feet.
1940	The Boulder Canyon Project Adjustment Act reduced repayment interest rates and established special funds for the study of water development.
1944	The Mexican Treaty guaranteed 1.5 million acre feet of water to Mexico
1949	The Upper Basin Compact adjudicated water rights between the upper basin states.

1956	The Colorado River Storage Project (CRSP) Act was passed, initiating construction of upper Colorado River basin water projects.
1957-63	Glen Canyon Dam construction, power production starts in 1964.
1968	The Colorado River Basin Project Act authorized construction of the Central Arizona Project, and created a special water development study fund for the lower Colorado River basin.
1970	The National Environmental Policy Act was signed.
1973	The Endangered Species Act was signed.
1974-76	The NPS coordinated the first ecological inventory of the Colorado River corridor in Grand Canyon (Carothers and Aitchison 1976), and the first sociological studies (REFS).
1980	Lake Powell filled to capacity for the first time.

1982	The Bureau of Reclamation rendered a Finding of No Significant Impact for the upgrading and rewinding of Glen Canyon Dam generators on the Colorado River corridor downstream.
1982	Secretary of Interior ordered the Bureau of Reclamation Glen Canyon Environmental Studies Program to conduct studies of dam effects.
1983	Largest post-dam flow (2,724 m^3/s) released from dam, damaging spillways.
1983-89	Forty studies of dam effects conducted during exceptionally high inflow and unanticipated spillway release flooding. Cooperating agencies conclude that GCES Phase I (Bureau of Reclamation 1988) showed: (1) dam affects river ecosystem, but (2) more data were needed on low and fluctuating flows.
1987	The National Academy of Sciences (NAS) reviewed of GCES Phase I (Marzolf 1987).
1989	The Secretary of the Interior ordered an ex post facto EIS on dam operations; initiation of GCES Phase II to support EIS preparation.

1990-91	GCES test releases were used to determine effects of individual flow regimes.
1991	Interim flows (low hourly change in flow) were implemented to protect river resources while the GCD-EIS was completed; the NAS conducted a Santa Fe "state of knowledge" symposium (Marzolf 1991).
1992	NAS "Delphi Process" symposium was held in Irvine, CA to plan long-term monitoring for the Colorado River ecosystem; the Grand Canyon Protection Act was passed, providing for the speedy resolution of the GCD-EIS and required balancing environmental protection of the river with economic benefits from the dam; Interim Flows monitoring was implemented.
1994	The Draft GCD-EIS was released to the public. Of the nine alternatives, the Preferred Alternative called for (1) low flow fluctuations to preserve tributary derived bed sand, (2) occasional planned flooding to restore higher elevation sand bars, (3) implementation of a long-term monitoring program, and (4) development of an adaptive management approach for future management based on cooperative, interagency discussion. The Cooperating Agencies requested that the U.S. Fish and Wildlife Service prepare a Biological Opinion.

1995	The Final GCD-EIS was submitted to the Secretary of the Interior.

Table 2: Impoundment-related changes in the Colorado River ecosystem following completion of Glen Canyon Dam in 1963.

RESOURCE OR PROCESS	PRE-DAM CONDITION	POST-DAM CONDITION
	PHYSICAL CHANGES	
Hydrology	Large, short duration spring and some summer floods with little daily change in stage.	Small, few long-duration floods, with large ($\geq$ 3m daily flow fluctuations.
Sediment Transport	Mean sediment transport $\geq$ 60 million mt/yr transported past Lees Ferry with cyclic deposition and erosion of sandbars whose distribution was controlled by debris fans	Little sediment transport past Lees Ferry, and < 5 million mt at Phantom Ranch derived from the Paria and Little Colorado rivers; erosion without replenishment.

Water Quality	High turbidity (little benthic PAR), seasonally warm (0–29°C) flow.	High water clarity in upstream reaches; cold-stenothermic flows (8°C at Lees Ferry, up to 16° at Diamond Creek in mid-summer)

BIOLOGICAL CHANGES

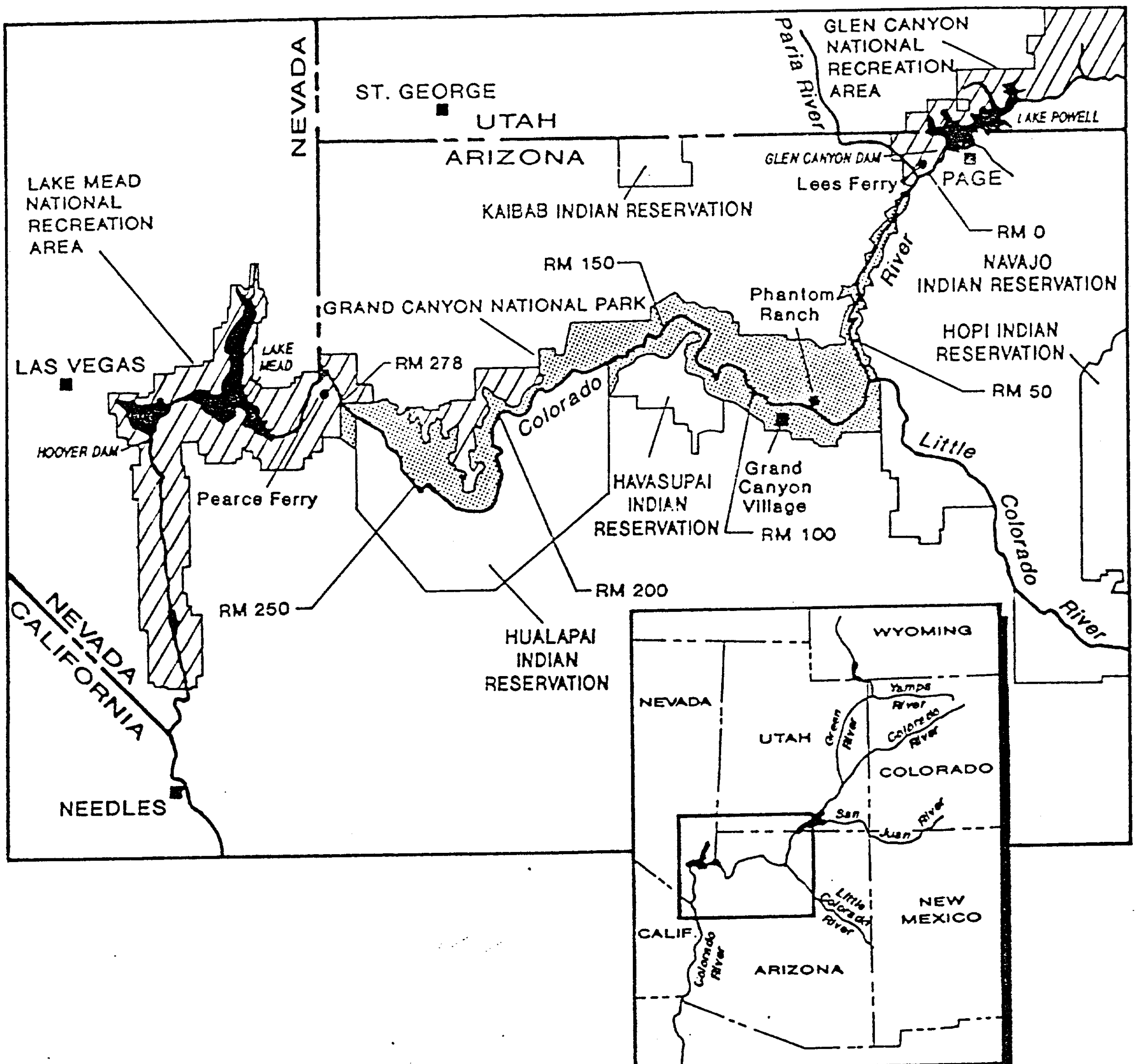
AQUATIC DOMAIN		
Benthos	Little algae apparent on pre-dam photographs; invertebrates probably restricted to firm substrata, but no pre-dam data.	High algal and invertebrate production in clear tailwaters, decreasing in turbid reaches downstream; low invertebrate diversity (no thermal emergence cues).

Fisheries	Highly endemic fauna, 8 species; negative impacts of pre-dam introduced fish species; migration of Lower Basin Colorado River squawfish blocked by Hoover Dam in 1929; tributary mouth ponding during spring floods; mainstream backwater habitats restored by annual floods.	Three of 8 native species extirpated; additional non-native species (19 total) introduced; little tributary mouth ponding; backwater habitats not restored because of reduced sediment transport and flood control.
Avifauna	Little winter presence; some tributary mouth breeding during spring, but virtually no mainstream breeding.	Winter concentration of waterfowl and bald eagle in upper reaches; summer mainstream breeding in upper reaches. Abundant waterbirds support the highest concentration of breeding peregrine falcon in 48 coterminous states.

Mammals	Beaver and otter present	Otter virtually extirpated, muskrat introduced?
RIPARIAN DOMAIN		
Hydro-Riparian Zone	Few if any fluvial marshes because of annual scouring floods.	Rapid development of fluvial marshes throughout river corridor.
Lower Riparian Zone	Little lower riparian zone phreatophyte vegetation because of annual scouring floods.	Rapid colonization of profuse, largely non-native (e.g. salt-cedar) riparian vegetation, with subsequent succession towards native species; extensive colonization of vegetation by reptiles, Neotropical migrant birds, and rodents.
Upper Riparian Zone	Low diversity woody phreatophyte strandline vegetation on upper terraces.	Little recruitment of pre-dam vegetation may lead to gradual loss.

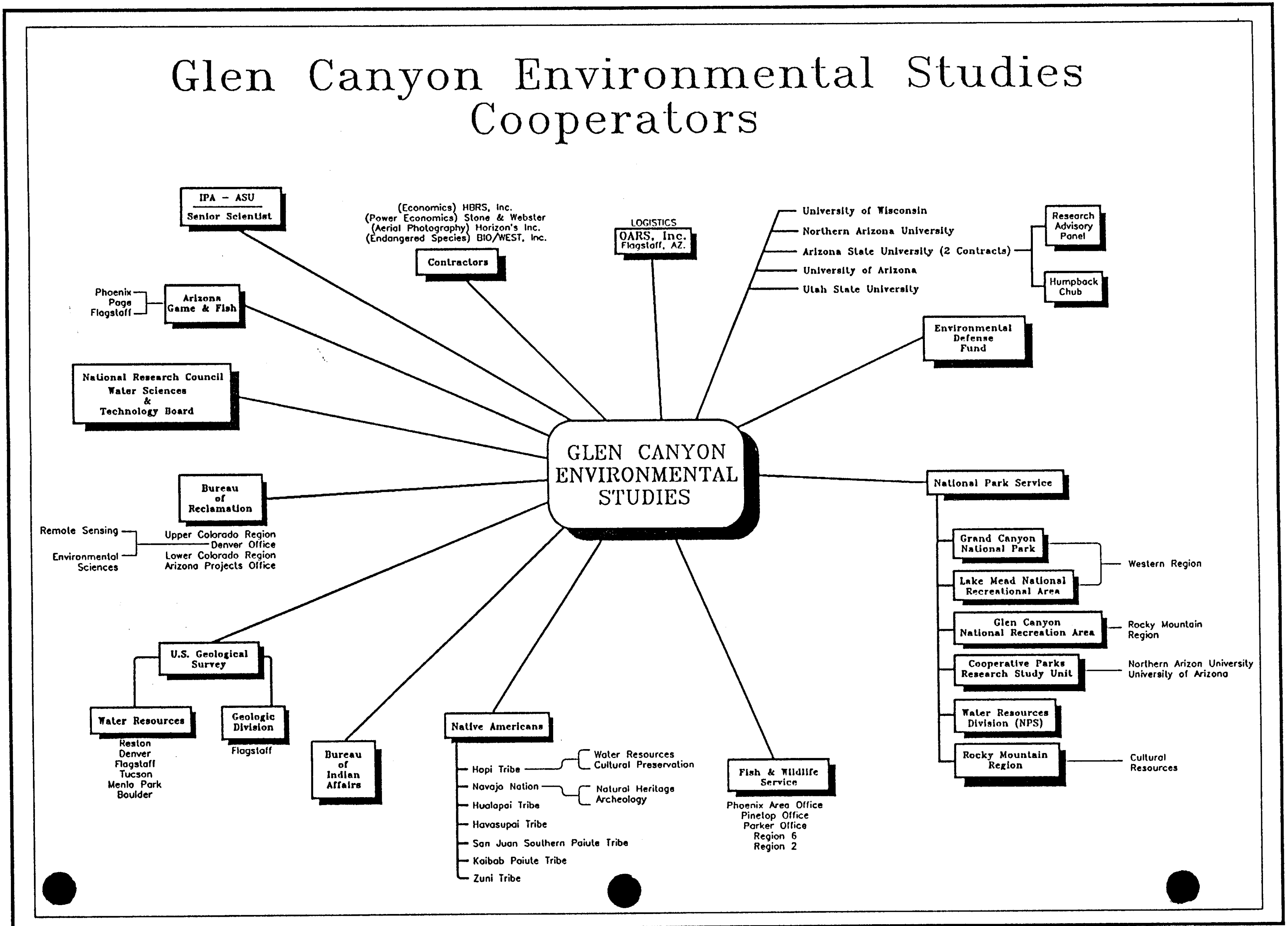
LIST OF FIGURES

FIGURE 1



GLEN CANYON NATIONAL RECREATION AREA
Paria River
NEVADA
ST. GEORGE
UTAH
ARIZONA
LAKE POWELL
GLEN CANYON DAM
Lees Ferry
PAGE
LAKE MEAD NATIONAL RECREATION AREA
KAIBAB INDIAN RESERVATION
RM 0
River
NAVAJO INDIAN RESERVATION
RM 150
Phantom Ranch
GRAND CANYON NATIONAL PARK
HOPI INDIAN RESERVATION
LAS VEGAS
LAKE MEAD
RM 278
Colorado
RM 50
HOOVER DAM
Little Colorado River
Pearce Ferry
HAVASUPAI INDIAN RESERVATION
Grand Canyon Village
RM 100
RM 200
RM 250
NEVADA
CALIFORNIA
HUALAPAI INDIAN RESERVATION
NEEDLES
WYOMING
NEVADA
UTAH
Green River
Yampa River
Colorado River
COLORADO
San Juan River
Little Colorado River
NEW MEXICO
CALIF.
Colorado River
ARIZONA

FIGURE 2



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(Economics) HBRS, Inc.
(Power Economics) Stone & Webster
(Aerial Photography) Horizon's Inc.
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Flagstaff, AZ.
University of Wisconsin
Northern Arizona University
Arizona State University (2 Contracts)
University of Arizona
Utah State University
Research Advisory Panel
Humpback Chub
Environmental Defense Fund
Phoenix
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Flagstaff
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National Research Council
Water Sciences & Technology Board
Bureau of Reclamation
Remote Sensing
Environmental Sciences
Upper Colorado Region
Denver Office
Lower Colorado Region
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Lake Mead National Recreational Area
Western Region
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Native Americans
Hopi Tribe
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Region 6
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